Report of Investigations 8295

Methane Drainage: Experience With Hydraulic Stimulation Through Slotted Casing

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UNITED STATES DEPARTMENT OF THE INTERIOR
Cecil D. Andrus, Secretary

BUREAU OF MINES

This publication has been cataloged as follows:

Lambert, Stephen W

Methane drainage : experience with hydraulic stimulation through slotted casing / by S. W. Lambert and M. A. Trevits. [Washington] : U.S. Dept. of the Interior, Bureau of Mines, 1978.

16 p. : maps, diagrs. ; 27 cm. (Report of investigations - Bureau of Mines ; 8295)

Bibliography: p. 14.

1. Methane. 2. Mine gases. 3. Mine drainage. I. Trevits, Michael A., joint author. II. United States. Bureau of Mines. III. Title. IV. Series: United States. Bureau of Mines. Report of investigations - Bureau of Mines ; 8295.

TN23.U7 no. 8295 622.06173

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ILLUSTRATIONS

METHANE DRAINAGE: EXPERIENCE WITH HYDRAULIC STIMULATION THROUGH SLOTTED CASING[1]

by

Stephen W. Lambert[2] and Michael A. Trevits[2]

ABSTRACT

The Bureau of Mines examined the wellbore of a vertical gas drainage well in the Mary Lee coalbed to determine the results of specific completion procedures in coal. A jet-slotting tool was used to cut four vertical slots through the casing about 1 ft below the coalbed. Even though stimulation treatment pressure was excessive, hydraulically induced channels were contained entirely within the target coal zone. Sand-filled, induced channels were horizontal, inclined, and vertical, and were propagated in directions similar to bedding planes, rock joint, and coal cleat directions measured in the mine. Variable gas flow rates, recorded during the productive life of the well, were attributed to chronic downhole pump malfunction and the slotted casing below the production zone.

INTRODUCTION

The purpose of this Bureau of Mines research was to test specific hydraulic stimulation procedures in coal by monitoring well production and to later inspect the results directly underground in the mine. A vertical degasification borehole that had been drilled in the Mary Lee coalbed and completed 600 ft ahead of active mining was intercepted on February 15, 1977. The borehole, referred to as test well No. 2 (TW2), is located in section 35, R 18 S R 6 W, near Oak Grove, Ala.; it is the second such borehole to be examined underground in the area.

A roller bit and foam were used to penetrate the coalbed to minimize wellbore damage. After the casing was set in the hole, the coalbed was exposed for stimulation using a jet-slotting tool. Density logs were used to identify slotted portions of casings and to identify zones within the coalbed that could have an influence on the geometry of hydraulically induced channels. The hydraulic forces used to stimulate the coalbed were diverted several times, resulting in numerous short channels. Horizontal channels were propagated when injection pressure exceeded effective overburden pressure.

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[1] The work described in this report was performed by a component of the Bureau of Mines that was transferred to the Department of Energy on Oct. 1, 1977.
[2] Geologist.

It is indicated that because of the relative softness of coal, the principal mechanism leading to horizontal channel development is compression rather than the flexing and lifting of all the overburden. Also, there is a direct correlation between propagated vertical channel directions and the joint and cleat orientations, and a direct relationship between surface and underground fractures. These relationships can be used to determine the direction of the vertical channel before stimulation.

DRILLING, COMPLETION, AND PRODUCTION

TW2 was rotary-drilled using a 6-1/4-in-diam air-percussion bit to approximately 235 ft above the 5-ft-thick coal interval. To reduce the possibility of formation damage caused by drilling, a 6-1/8-in-diam roller bit was used to drill the remaining distance to 50 ft below the coalbed. TW2 was cased to total depth with 4-1/2-in-outside-diam (OD) pipe. The lower 500 ft of casing was set in place using 13.8 lb/gal cement.

A jet-slotting tool was positioned using a geophysical logging device. The design called for a water and sand slurry to cut four vertical slots, 90° apart, from the base of the coalbed to within 1 ft of the top. The coalbed was stimulated using 3,500 gal of a highly viscous fluid containing 4,000 lb of 10/30- and 20/40-mesh sand.

The hydraulic stimulation pressure averaged 2,400 lb/sq in gage with no apparent formation "breakdown," the fluid injection rate averaged 8 bbl/min, and the instantaneous shut-in pressure was 2,200 lb/sq in gage (fig. 1). After stimulation, water was circulated in the well removing approximately 200 lb of propping sand. The well was equipped with a pump to remove water and with meters to monitor production.[3]

TW2 was put on production November 13, 1976. During successful pumping periods, daily gas production averaged about 15,000 cu ft. Sand and other foreign material entering the downhole pump mechanism caused chronic malfunction and resulted in overall poor gas production (fig. 2). This malfunction made it necessary to dismount the pump and remove the material before water production could be resumed. Immediately after servicing the downhole pump and after removal of usually less than 5 bbl of water, temporary gas flow rates in excess of 80,000 cu ft/day were measured on several occasions. Such high gas flows appear to have brought significant amounts of propping sand into the wellbore.

[3]For details of drilling and completion of TW2, see the appendix.

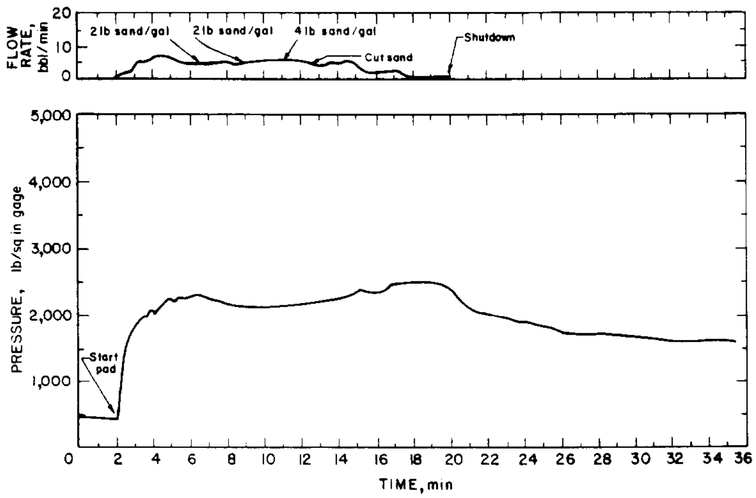


FIGURE 1. - Hydraulic stimulation pressure and fluid injection chart, TW2.

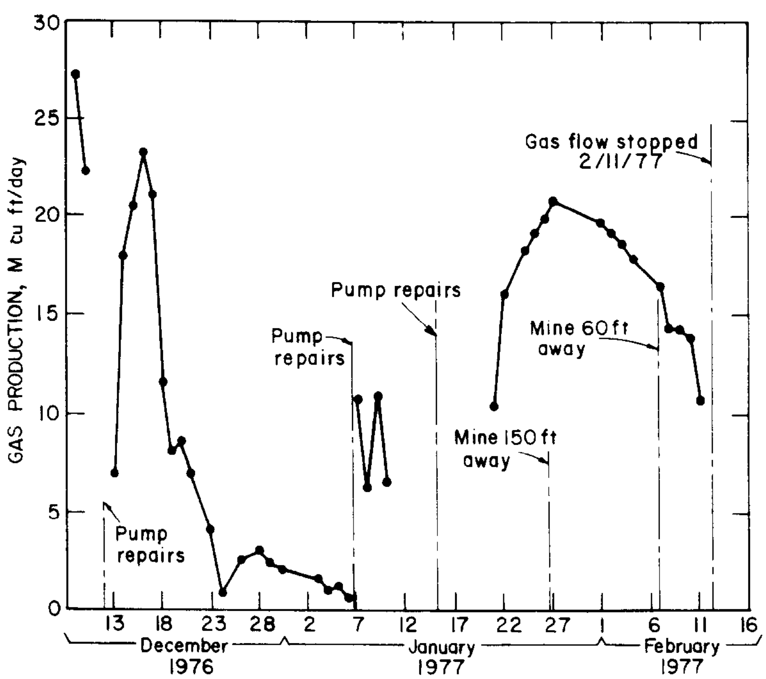


FIGURE 2. - Daily gas production from TW2.

MINE INVESTIGATION

A survey of fracture orientations in the coal and roof rock was conducted within an area of the mine near TW2. Physical characteristics of the coal and associated rock strata were noted during the survey. After borehole interception, the physical condition of the casing and wellbore and the geometry and orientation of hydraulically induced partings were studied in detail.

Fracture Survey

A mine survey was conducted to determine if hydraulically induced fractures had propagated in directions parallel to existing natural fracture trends. In an earlier study, at test well No. 1 (TW1), a correlation was made between cleat and joint directions and fractures believed to have been induced or extended by drilling, cementing, and stimulation.[4]

The area of the mine near TW2 is divided into seven stations (fig. 3). A compass was used to measure the direction of all visible roof joints and at least 15 coal cleats within each station. Directions of all observed hydraulically induced fractures containing prop sand were also measured. All measurements were adjusted for magnetic declination and then plotted on rose diagrams (fig. 4).

[4]TW1, completed approximately 500 ft from active mining, was hydraulically stimulated Nov. 23, 1975, using 5,000 gal of fluid and 2,500 lb of sand.

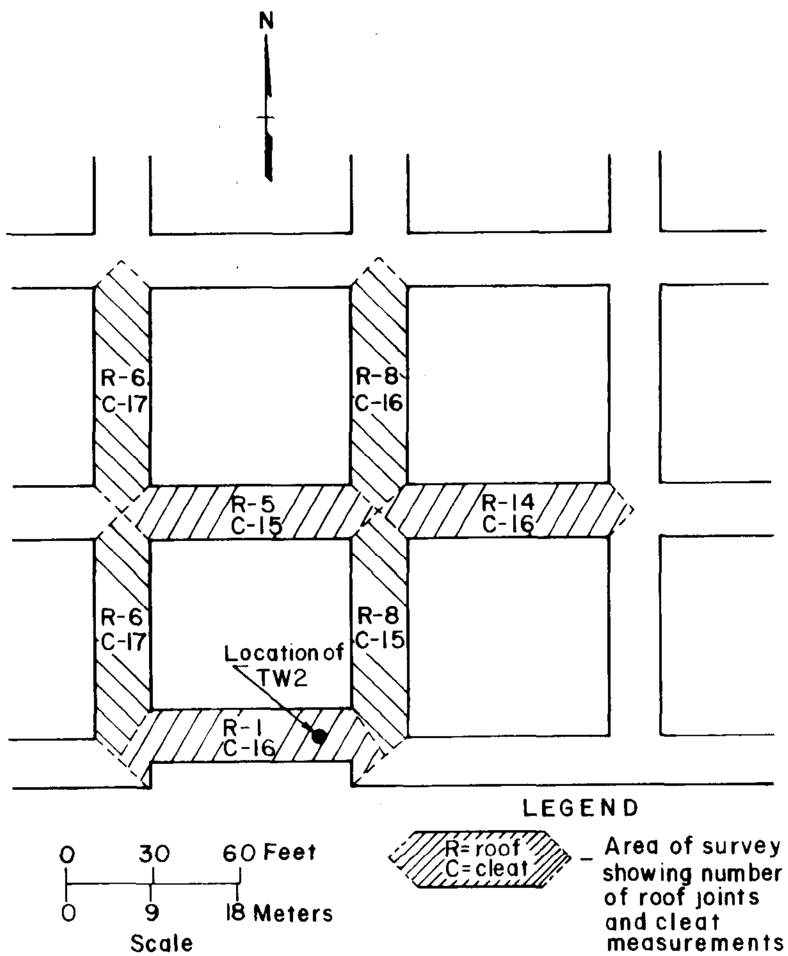


FIGURE 3. - Survey stations dividing area of mine near TW2.

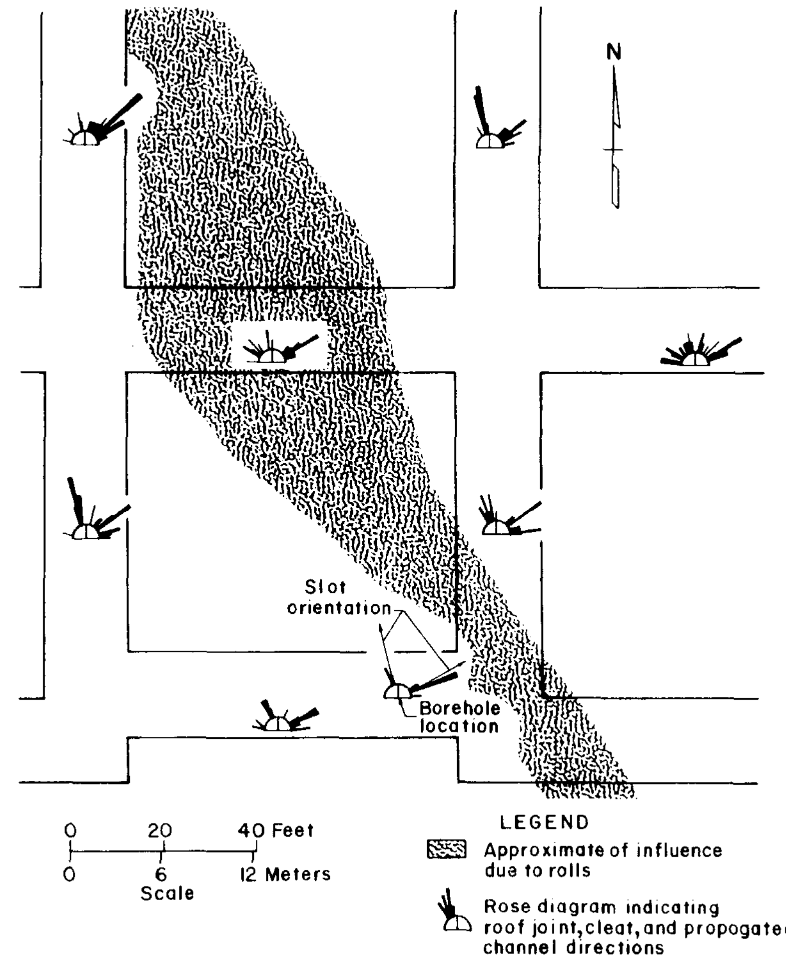


FIGURE 4. - Roof joint, cleat, and hydraulically induced channel directions near TW2.

Prominent linear features commonly called "rolls" are present in the mine approximately 20 ft northeast of TW2 trending roughly N 35° W. These rolls are expressed in the roof rock as troughlike features where the underlying coal thins abruptly. Coal and roof rock within and along the flanks of the rolls are highly slickensided with badly distorted bedding planes.

The upper 3-ft portion of the coalbed in the area studied, including the borehole site, was highly sheared and appeared to be generally friable and soft. The lower 2 ft of coal was considerably harder with well-developed, closely spaced cleat.

Description of TW2

TW2 and induced sand channels were exposed by a continuous-mining machine extracting coal eastward. Coal was removed to approximately 4 ft beyond the borehole location where there were very wide, short, vertical channels and longer, thin, horizontal, sand-packed channels. After bolting the roof, the site was studied in detail and measurements were made with the coal face in the position shown in figure 5; the borehole site and coal face at that time are shown in figure 6.

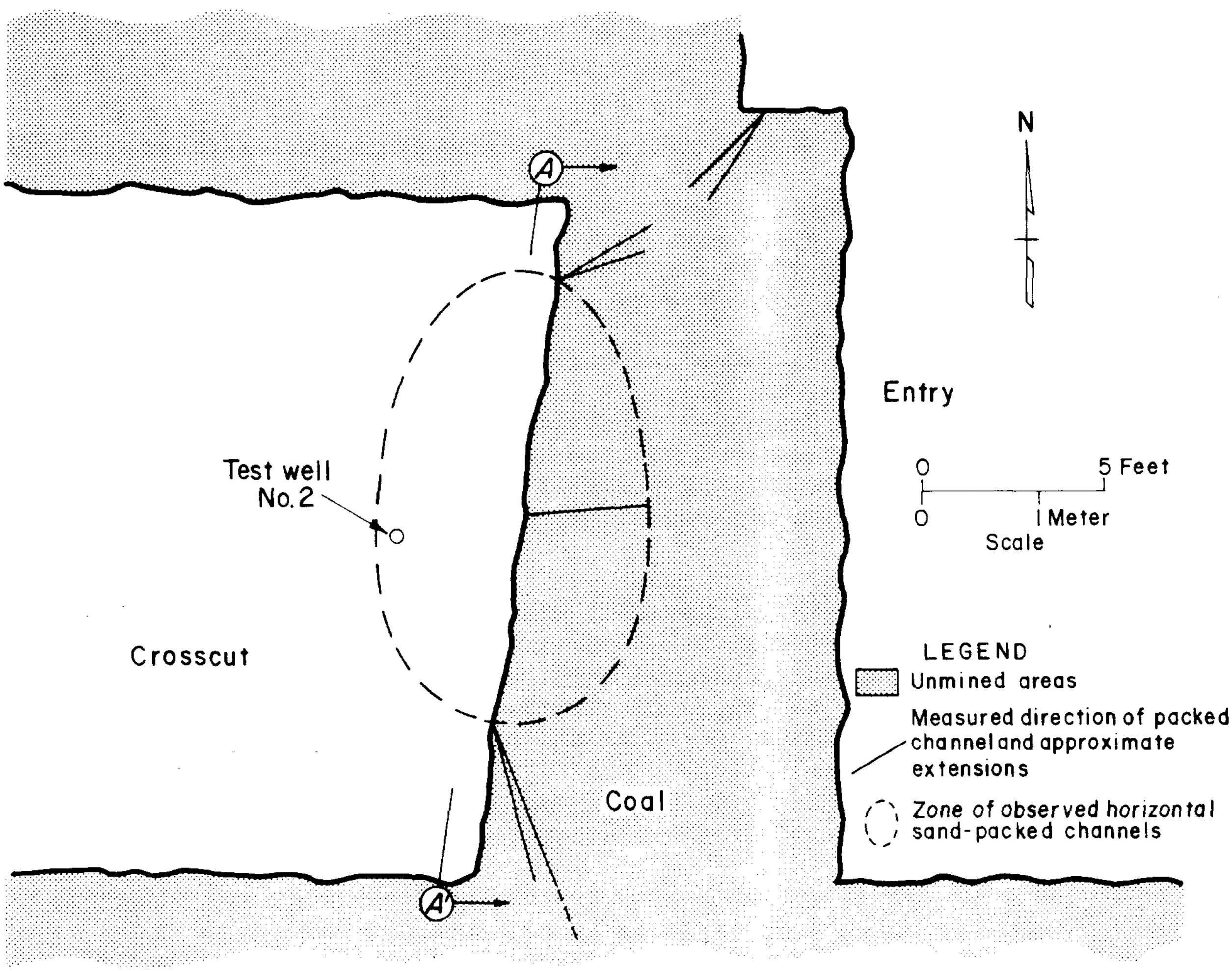


FIGURE 5. - Position of mine face during underground examination of TW2.

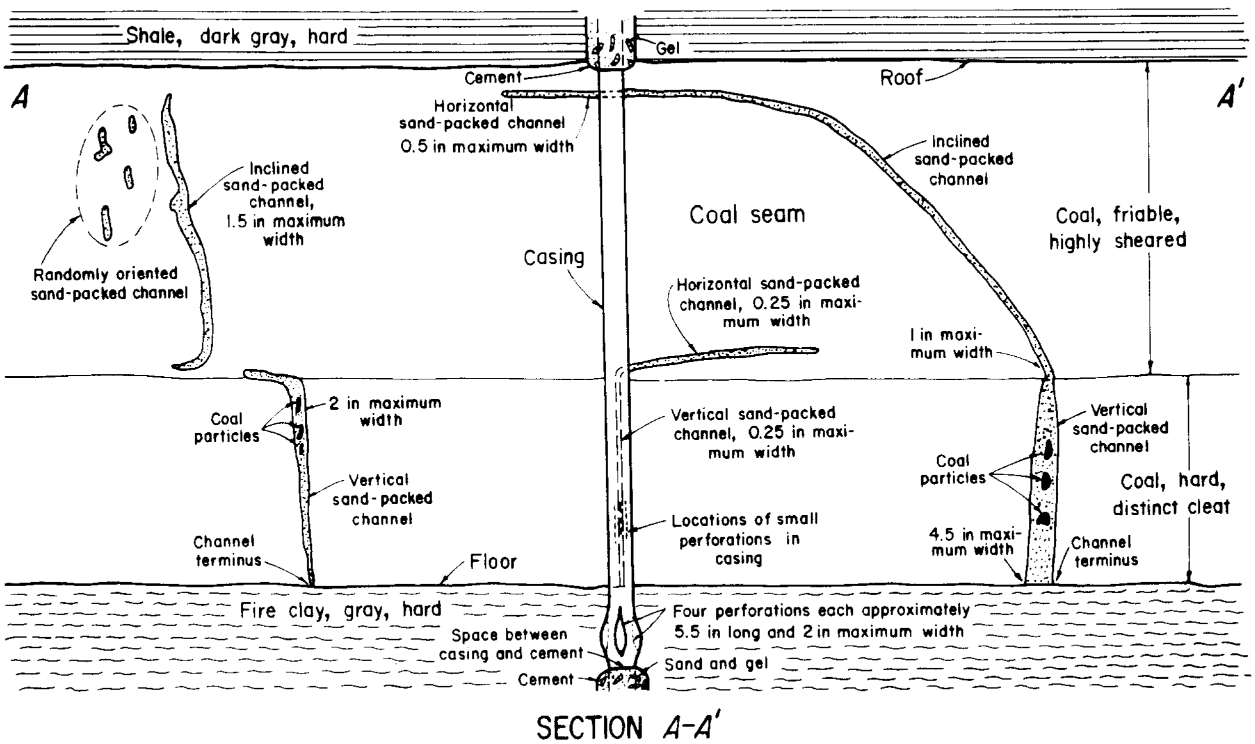


FIGURE 6. - Sketch of mine face during underground examination of TW2.

Wellbore Observations: Hard cement was observed to fill the northern half of the 1-in space between the casing and the drill hole in the roof and floor. No cement was found in the southern half of the wellbore; instead prop sand and/or gel filled this annular space at both the floor and the roof.

The casing was expanded outward, where it was pierced by four roughly diamond-shaped slots about 5.5 in long and 2 to 2.5 in wide. Five holes (0.3-in maximum diameter) in the casing were 5 to 9 in above the slots. The tops of the slots were about 4 in below the base of the coalbed, and directions of the slots were N 60° E and N 15° W. No cement could be found on either side of the casing exposed within the coal interval.

Induced Hydraulic Channels: Three well-defined vertical channels at the borehole site were contained in the lower third of the coalbed, and they were completely filled with propping sand. The channel sides appeared smooth and unabraded, and they followed local vertical fracture planes in the coal. The widest channel (4.5 in), located south of TW2, tapered upward gradually; a 2.0-in-thick channel, north of the borehole, tapered sharply to the floor; the remaining vertical channel, located directly behind the exposed casing, was 0.3 in throughout. All three channels terminated at the base of the coalbed with no evidence of fracture continuation into the floor rock.

Two channels sloped downward to the south and were contained entirely in a more friable, soft, and highly slickensided portion of the coalbed. Their sides were smooth and unabraded but somewhat irregular; they appeared to follow local shear fracture planes in the coal, with minor vertical development along cleat planes. The shape and downward extension of these channels indicate direct or inferred continuation with the vertical channels described earlier.

Four horizontal channels appeared at the coal face as extensions of either vertical or inclined channel development; all four occurred along bedding planes. Three of the channels were present approximately one-third of the distance up from the floor near the line of contact between hard, distinctly cleated coal and soft, friable, sheared coal. The fourth horizontal channel ran along a line 6 in below the coal-roof-rock interface; coal immediately surrounding the horizontal channels was very soft and appeared crushed.

Four small, separate, randomly oriented, sand-filled channels were in the upper portion of the coal face north of the wellbore. Their locations indicate close association with a system of larger channels trending approximately N 65° E. These channels were along shear, cleat, and bedding planes, and thus possessed characteristics of all three channel types described earlier.

DISCUSSION OF RESULTS

Drilling

There was no evidence that drilling adversely affected the coalbed or surrounding rock strata. Except for hydraulically induced partings in the coal, the only opening in rock leading directly from the wellbore was a well-developed roof joint which was believed to have opened sometime after TW2 was completed because it did not contain cement or propping sand.

Cementing

The lightweight, low-fluid-loss cement mixture, together with the low injection rates used to stabilize casing in the borehole (see appendix), prevented excessive permeability damage to the coalbed. No evidence of cement infiltration was found in the floor, coal, or roof rock.

The cement bond to casing was generally poor. For example, the mining machine which exposed the borehole never came in direct contact with the casing or cement, so the cement, if ever present, must have been pulled from the casing leaving no residue as coal surrounding the test well fell away under its own weight. The lack of cement within approximately one-half of the wellbore annulus in the roof also indicates poor cementing.

Logging

A comparison of density logs with underground observations shows the logs to be an important tool for predicting coalbed characteristics. All density logs clearly indicate two major density zones within the coalbed (fig. 7).

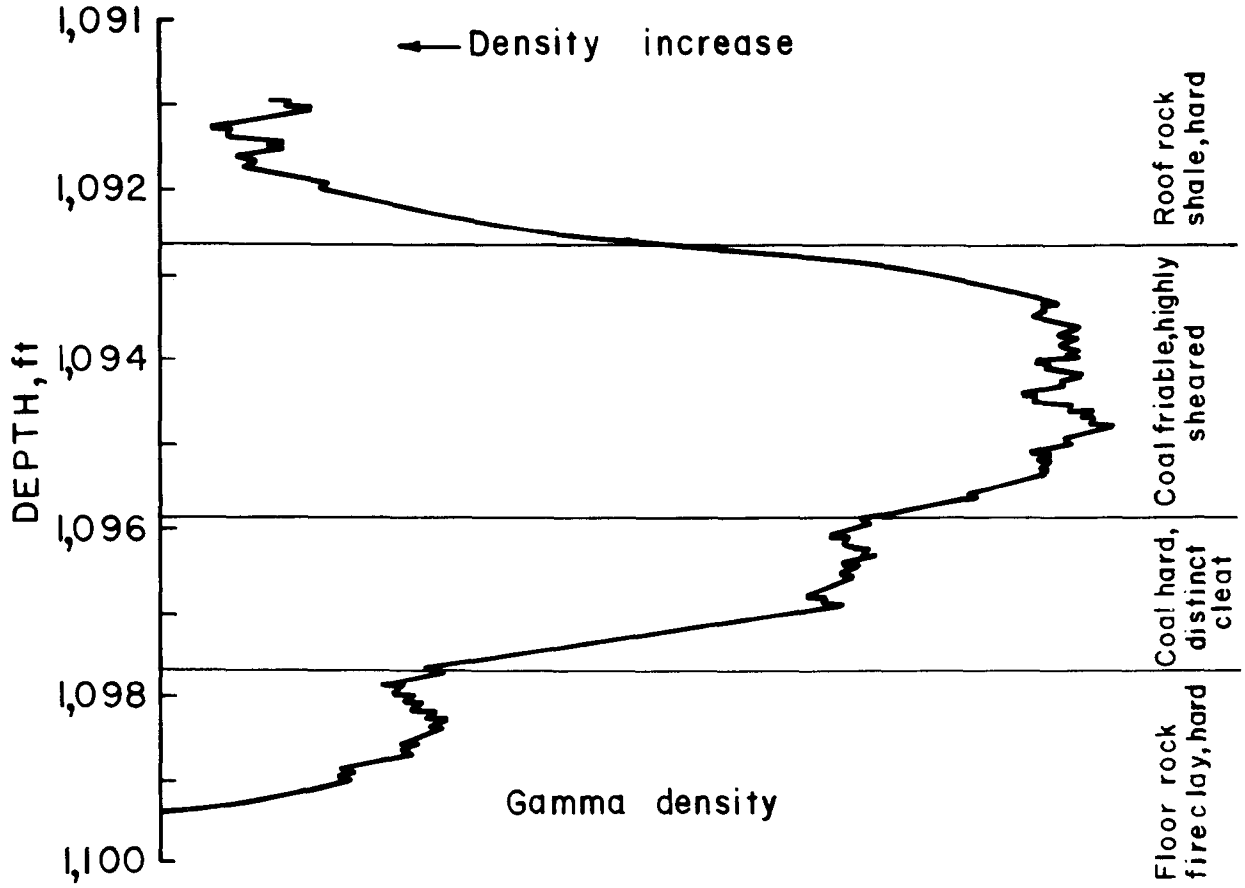


FIGURE 7. - Portion of density log from TW2 compared with rock strata observed underground (log run before casing was slotted).

The upper, less dense zone correlates precisely with the friable, highly sheared portion of the coalbed containing all induced channels that were inclined or horizontal. The denser, lower zone on the log locates the interval of hard, distinctly cleated coal containing induced, vertical channels.

Jet Slotting

Using density log information, the base of the coalbed was determined to be 1,099.2 ft deep, and four vertical slots, each 48 in long, were to be cut at that depth. Subsequent logging revealed that the base of the coalbed was actually 1,098.4 ft deep, and that jet slotting had begun below the coal.

If the casing had been cut throughout the prescribed length, the fact that the slots began several inches below the coalbed would have been of little consequence. However, as observed underground, the casing had not been penetrated throughout the entire coal interval. Factors that may have contributed to poor slotting results include insufficient time allowed to cut the casing; slight rotation or twisting of the tool could have occurred as it was raised and lowered through the prescribed interval (at least two heavily abraded, vertically oriented "tracks" were noted along inner surfaces of casing exposed to each jet nozzle), and the very soft, friable nature of the coal could have absorbed much of the cutting "energy" (all perforations through casing occurred either in the hard floor rock or in the hard lower portion of the coalbed).

Close examination of density logs taken before and after slotting operations indicated that the small section of pipe successfully cut could have been recognized before actual underground observations. Logs taken after slotting show a significant density decrease along the interval of borehole directly exposed to rock strata (fig. 8).

Stimulation

The treatment used to stimulate TW2 was designed to induce vertical, 1-in-wide, sand-filled channels in two directions from the wellbore. Each channel was to be approximately 150 ft long and just under 5 ft high. Based on prior underground observation at the TW1 site, channels were expected to propagate in directions similar to existing natural fractures in the coal.

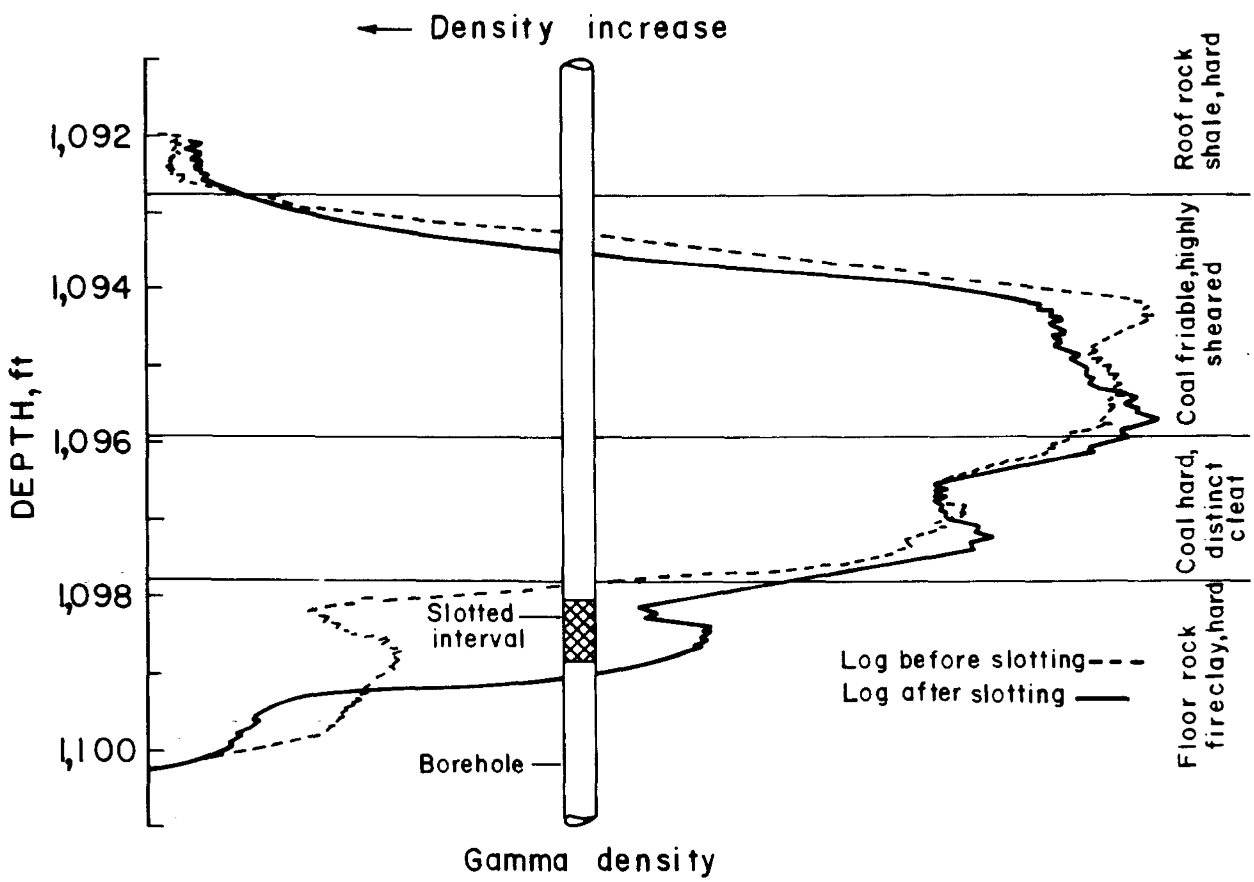


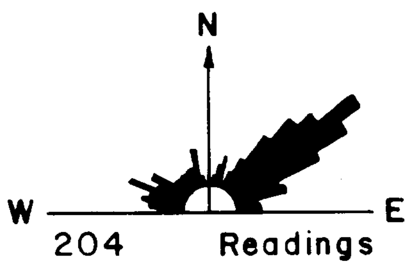
FIGURE 8. - Comparison of density logs run before and after slotting.

Previous work on stimulating the Mary Lee coalbed (1)[5] indicated that formation breakdown could be expected to occur below 900 lb/sq in.

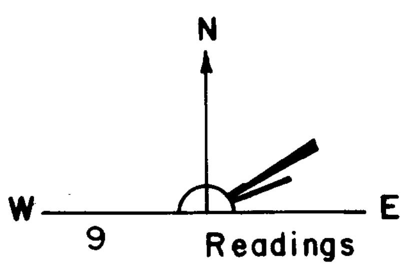
The sand channels hydraulically induced into the coalbed were horizontal, inclined, and vertical, making it difficult to determine the complete dimensions of each. However, figure 5 indicates that the maximum length of propagation from the wellbore was 50 ft or less, rather than the maximum 300 ft calculated in the original design.

The underground channels, especially the wide vertical channels, were generally composed of several smaller induced sand channels. The number of slightly different directions measured along the channel walls; the coal particles contained in these channels; and the number of small, randomly oriented, sand-filled channels all indicate a complex system of propagated channels along closely spaced vertical planes (as cleat planes). Instead of one or two extended directions, the hydraulic force used to propagate fractures in the coal is believed to have been diverted several times in slightly different directions during high-pressure pumping. This apparently resulted in numerous short channels rather than in one or two continuous long channels as predicted in the design.

Results of the underground vertical fracture (fig. 4) show a direct correlation between propagated channel direction and joint and cleat orientation. Findings from a previous underground study at TW1 yielded similar results which are shown in figure 9. Although sand-filled channels were not observed at TW1, there is sufficient evidence to indicate that partings in the coal and roof rock had been opened during drilling, cementing, and early stages of stimulation.



Roof joint and cleat direction in mine area of No.1 Test Well.



Partings, induced or extended from Test Well No.1 during drilling, cementing, and stimulation.

FIGURE 9. - Comparison of roof joint and cleat directions in mine area with fractures induced or extended during drilling, cementing, and stimulation of TW1.

[5] Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

Surface rock joint and coal cleat directions measured in an area overlying both test well locations (3) indicate a close correlation between the surface and underground fracture orientations of figures 4 and 9. Given the observed relationship of induced channel direction with existing underground and surface fracture orientation, it may be concluded that the direction of induced channel development can be predetermined, thus aiding future placement of coal gas wells in the area.

The most obvious explanation for the initial high treatment pressure during stimulation is that fluid was first exposed to hard fireclay, rather than to relatively soft coal. The high pressure that was maintained throughout the treatment is attributed primarily to the high viscosity of the treating fluid, and second, to the flow resistance created by the small openings in the casing.

When injection pressures exceed the overburden pressure horizontal channels may develop. Given a mean specific gravity of 2.5, the overburden pressure gradient should be about 1.06 lb/sq in/vertical ft (2). Since the depth to the coalbed at TW2 is 1,093 ft, horizontal channels could be expected to develop when injection pressures exceeded 1,160 lb/sq in. Treating pressures maintained throughout stimulation of TW2 were in excess of 2,200 lb/sq in gage (fig. 1).

Horizontally oriented sand-filled channels can result from one of two types of rock movement: The compression of rock in the vicinity of the fracture or the flexing and lifting of all or a portion of the overburden (4). The crushed appearance of coal surrounding the horizontal channels suggests that, in this case, compression of rock was the principal mechanism.

The loss of treatment fluid during propagation resulting in the premature drop of sand proppant is believed to have remained at a minimum during stimulation of TW2. Such "sand-outs" are not indicated on the treatment chart (fig. 1). Low fluid loss to the formation is also indicated by the extremely high pressures maintained in the wellbore after pumps were shut down.

Although injection pressures were as high as 2,500 lb/sq in during the stimulation treatment, there was no evidence of induced fractures in the roof or floor rock. Sand proppant and gel found in the wellbore annulus in the floor indicate direct exposure to treatment fluid under high pressure. In preference to fracturing the harder floor rock, fluid moved upward, near the casing, and into the coal zone before extending outward. A roof joint extending directly from the wellbore was believed to have opened sometime after stimulation since it contained no sand or gellike material.

The stimulation design provided for an enzyme-type breaker to considerably reduce the treatment fluid viscosity within a few days. Gel, however, was found around the casing in the roof and floor. The gel in the roof contained no sand and therefore must have been included in the initial fluid pad before the proppant was added. The gel around the bottom of the casing did contain sand and could have been placed there anytime during treatment.

Gel presence may be explained in two ways: Either the breaker was not added to the stimulation fluid as planned, or the breaker was added throughout treatment but chemical factors in both roof and floor prevented gel breakdown. The first explanation is unlikely; the second is more probable considering temperature variation, possible reaction with pipe, cement, etc.

Production

Two major factors responsible for the poor production at TW2 are heavy grease used to preserve downhole water production equipment was not completely removed before installation and repeatedly clogged the pump, and the position of slots below the production zone allowed water to drain from the coalbed but was not conducive to gas drainage. Since water drains to lower horizons of the coalbed, free gas is believed to have accumulated in the upper portions of the coal against the overlying impervious roof rock (shale).

During the first 3 days of successful pumping, TW2 produced no gas, although a significant volume of gas is thought to have accumulated in upper portions of the coalbed around the wellbore. On the fourth day the pump clogged with grease and was dismounted for servicing. The water level rose in the borehole as formation pressures partially recovered. Based on previous Bureau of Mines studies,[3] it may be assumed that free gas pressure equilibrated with the increasing hydraulic head.

The pump was repaired and water production resumed on the eighth day, and after removing approximately 4.3 bbl of water and measuring no flow through gaslines, the well "unloaded," suddenly producing gas at more than 80,000 cu ft/day. This indicates that the free gas pressure around the wellbore had built up during the previous 8 days and that it was suddenly released when pumping caused a disequilibrium pressure state between the coalbed and the wellbore. This sequence of events was repeated several times during the productive life of the well because the pump became inoperative following each unloading.

Gas production stabilized slightly during a 2-week interval prior to underground interception. Given the position of slots in the casing, stabilized gas production could not have been possible while significant amounts of water continued to flow through the coalbed. Waterflow from the well did, in fact, decrease during this period. Since experience with other coal gas wells in the Mary Lee indicates relatively stable waterflow over extended periods (1), it is believed that pumping did not significantly "dewater" the coalbed around the wellbore and that the reduction of water production rate was due to drainage of water into the approaching mine opening.

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[3] Recent laboratory experiments show conclusively that gas desorption from Mary Lee coal will continue at pressures in excess of 120 lb/sq in gage. Field studies indicate Mary Lee coalbed gas will continue to flow from new wells until a static water level is achieved.

CONCLUSIONS

1. Rotary drilling using roller bit and foam is an effective technique to avoid extensive wellbore and/or coalbed damage.

2. A lightweight, low-fluid-loss cement mixture can reduce cement infiltration into the floor, coal, and roof rock.

3. Density logs may be used to identify zones within coalbeds which may have a substantial influence on the geometry of hydraulically induced channels. Density logs may also be used to identify successfully slotted portions of casing.

4. The hydraulic forces used to stimulate coal may be diverted several times, resulting in numerous short channels rather than one or two continuous long channels. Horizontal channels may be propagated when injection pressure exceeds effective overburden pressure, but because of the relative softness of coal, the principal mechanism leading to horizontal channel development is compression rather than flexing and lifting of the overburden.

5. Underground fracture studies indicate a direct correlation between propagated vertical channel directions and the joint and cleat orientations. There is also a direct relationship between surface and underground fractures which can be used to determine the vertical induced channel direction before stimulation.

6. Gel may not break down sufficiently near the wellbore, because of low temperatures or adverse chemical reaction with casing materials.

7. Highly variable gas flow rates may be attributed to downhole water pump malfunction and/or to the positioning of production openings (slots or perforations) below the productive coal zone.

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APPENDIX.--HISTORY OF TEST WELL NO. 2 IN THE MARY LEE COALBED NEAR OAK GROVE, JEFFERSON COUNTY, ALA.

DRILLING			
Drilling depth, ft	Bit type	Bit diameter, in	Circulation medium
0 to 10.0	Tricone	8.75	Air.
10 to 857.0	Air percussion	6.25	Air-foam.
857 to 1,150.6	Tricone	6.13	Do.

CASING			
Casing, ft	Casing type	Weight, lb/ft	Casing diameter, in
0 to 10.0	Surface pipe	13.0	6.63
0 to 1,150.0	K-55	9.5	4.50

NOTE.--The lower bench of the Mary Lee coalbed is from 1,093.4 to 1,098.4 ft deep. TW2 is in section 35, T 18 S, R 6 W. Drilling was started September 26, 1976, and it was completed October 20, 1976, to a total depth of 1,150.5 ft. The total depth of the casing was 1,150.0 ft.

Cement

Date	October 21, 1976.
Zone cemented	650 to 1,150.5 ft.
Number of sacks	35.
American Petroleum Institute class	A.
Yield	1.44 cu ft per sack.
Mixed weight	13.8 lb/gal.
Additives	2 pct gel.
Do	10 lb gilsonite.
Do	4 lb salt.
Do	2 pct calcium chloride.
Circulating pressure	100 lb/sq in gage.
Displacement pressure	150 lb/sq in gage.
Maximum pressure	150 lb/sq in gage.
Treating rate	1 bbl/min.
Displacement rate	1 bbl/min.
Cement left in casing	15 ft.

Geophysical Logging

Date	October 23, 1976.
Type of log	Natural gamma, gamma density.
Interval logged	0 to 1,132 ft.
Do	1,012 to 1,130 ft.
Do	1,062 to 1,130 ft.
Date	October 27, 1976.
Type of log	Gamma density.
Interval logged	1,080 to 1,106 ft.
Do	1,066 to 1,105 ft.
Do	1,084 to 1,101 ft.
Do	1,082 to 1,105 ft.
Do	1,078 to 1,105 ft.

Slotting the Casing

Date	October 24, 1976.
Type of tool used	Jet slotting.
Abrasive medium	20- to 40-mesh sand.
Interval treated	1,094.4 to 1,098.4 ft.
Perforations, type, spacing	4 slots, 90° apart.

Hydraulic Stimulation

Date	October 24, 1976.
Propping sand	20- to 40-mesh sand, 1,000 lb.
Do	10- to 20-mesh sand, 3,000 lb.
Treatment fluid	Gelled water, 3,500 gal.
Surfactant concentration	3 gal/1,000 gal.
Fluid-loss additive concentration	50 lb/1,000 gal.
Gelling agent concentration	66.7 lb/1,000 gal.
Breaker concentration	2 lb/1,000 gal.
Complexer concentration	0.4 gal/1,000 gal.
Maximum pressure	2,500 lb/sq in gage.
Average pressure	2,400 lb/sq in gage.
Treatment rate, average	8 bbl/min.
Hudraulic horsepower	1,000 hp.

Well Life

Date production equipment installed	November 12, 1976.
Date production began	November 13, 1976.
Date production equipment removed	February 14, 1977.
Date underground interception	February 15, 1977.

U.S. GOVERNMENT PRINTING OFFICE: 1978-703-103/58

INT.-BU.OF MINES,PGH.,PA. 23146